An Experimental Research Platform Architecture for UAS Communications and Networking

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***Abstract*—New use cases for advanced wireless technologies are emerging in the unmanned aerial systems (UAS) spaces. These put pressure on technology and regulation. The way to overcome this is to gain experience and collect data while operating UAS in production environments. To this end, we introduce AERPAW: Aerial Experimentation and Research Platform for Advanced Wireless, and present an architecture for designing a large-scale community testbed in a production-like environment to enable controllable experiments with latest wireless technologies and systems. Using advanced networking and virtualization technology to manage the platform resources, users will be able to configure the testbed for running a variety of at-scale experiments for UAS localization and tracking, networking, trajectory optimization, spectrum management, and aerial-terrestrial cellular network design and optimization based on 5G and software radio technology, among others.**

Keywords–Testbed, Drones, UAS, 5G, IoT, SDR.

I. Introduction

Advances in wireless communications and networking technology now enable ubiquitous mobility with broadband connectivity in three dimensions. In addition to ground-based mobility services, such as vehicle-to-vehicle communications and mobile virtual and augmented reality (VR/AR), new use cases for advanced wireless technologies are emerging in the unmanned aerial systems (UAS) spaces with unprecedented opportunities in the commercial, government, civil, and military sectors. Multiple applications of UAS have attracted major attention, e.g., by Amazon, Google, Uber, Boeing, Zipline, Flytrex, and Matternet. While most UAS operations presently require visual line-of-sight (VLOS) between a pilot and the drone, cellular networks with advanced wireless technology will enable beyond VLOS (BVLOS) and autonomous UAS operations [1]–[3], unleashing autonomous 3D mobility.

Wireless testbeds allow existing technology to be analyzed for new use cases [4], or new wireless connectivity and networking principles to be explored and new protocols to be designed, developed and tested [5]. A testbed is an invaluable tool for researchers and developers to be able to integrate and experimentally evaluate research advances in realistic operational conditions. But because of major difficulties in conducting wireless research experiments with UAS (e.g., strict regulations and technological/social complexities for large scale experiments), most of the academic research on UAS communications is limited to simulations and theoretical analyses, using models that are often too simple, unrealistic, and untested. Whereas some UAS communications and networking proposals have been experimentally tested, most of these experiments are for isolated use cases, are operated in confined environments, or serve specific purposes. Three dimensional, highly mobile, and diverse communication scenarios involving UAS require real world experiments. In this context, testing of the wireless communications and networking capabilities of heterogeneous UAS and swarms of UAS with or without terrestrial infrastructure support is much needed and, by and large, lacking. We therefore introduce *AERPAW: Aerial Experimentation and Research Platform for Advanced Wireless* [6]. AERPAW will have two major goals: (1) to accelerate the integration of UAS into the national airspace system (NAS); and (2) to enable new advanced wireless features for UAS and mobile platforms. AERPAW's unique testing environment will support emerging technologies such as millimeter-wave (mmWave) systems and massive Internet of things (IoT) connectivity to realize unforeseen broadband applications and accelerate advances of autonomous transportation systems.

We will consider both use cases of UAS: (1) UAS as cellular user equipment (UE), and (2) UAS as cellular base stations (BSs) serving other users on the ground and in the air. Apart from experimenting with a wide range of communication problems (see Section II), a major feature of the envisaged platform will be the detection and tracking of unauthorized UAS using radar techniques and radio frequency (RF) signals radiated from UAS/controllers. Additional benefits include improved communications with advanced wireless systems for situational awareness, broadband connectivity, airspace access, and system safety. Situational awareness is critical for public acceptance, law enforcement, and autonomous system operation, whereas communications will enable airspace access through air traffic management, authorization analysis, and deconfliction. Protecting the integrity of the air transportation system is essential for maintaining safety, which is performed through communicating plans, actions, and intentions.

The remainder of this paper is organized as follows. Section II discusses the pressing research needs for UAS connectivity. Section III provides an overview of the AERPAW architecture and its logical system components. We describe the radio equipment and how they facilitate advanced wireless experiments with UASs in Section IV. Section V concludes the paper.

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II. Research & Development on UAS Connectivity

The envisioned platform needs to be able to serve the advanced wireless and UAS research and development (R&D) communities. We therefore conducted an extensive literature survey and identified several current research topics in Table I, where initial research results have been reported based on theoretical analyses, simulations and, to a limited extent, experimentation. We also conducted a broad user survey among global researchers. Out of 71 responses, 51 are from professors, 6 are from graduate students, and the rest includes people from industry, Idaho National Labs, NASA, and the German Aerospace Center. Survey outcomes show that having (1) access to training tutorials/videos, (2) the ability to reserve the testbed, (3) the ability to access the platform through multiple means, and (4) full remote access to software-defined radios (SDRs) are some of the key features desired by the survey respondents. There was significant interest to use SDRs, both at cell towers and, more critically, at the UAS. Having access to mmWave SDRs and 5G New Radio (NR) mobile phones carried by the UAS were also highly demanded. For UAS applications, search and rescue, detection and tracking, and the use of UAS as a hot spot BSs received the highest interest.

Additional experimentation possibilities were suggested by the survey takers. These include mobile VR/AR, the use of wireless communications for control/guidance of multi-agent networks, e.g. in micro-grid scenarios, energy endurance of aerial platforms, reflection measurements from ground/clutter, wireless energy transfer from UAS to distant sensors, multi-connectivity with UAS, high resolution imaging/surveying, UWB localization/communication, design of computational and energy efficient protocol stacks, dynamic/adaptive bandwidth allocation to support UAS search and rescue operations, design of multi-band and multi-function RF/microwave/mmWave components/circuits, and extended UAS command and control using cellular and wireless local area networks.

TABLE I
Aerial wireless research challenges.

Challenge	Description and representative papers
mmWave communications	Aerial communication/propagation at different mmWave frequencies, link distances, speeds, and environmental conditions [7], [8].
3D antenna design and aerial MIMO	Single/multiple antenna structures to support full 3D coverage and UAS maneuvers [9], [10].
Wireless-aware trajectory design	Seamless, reliable, autonomous UAS connectivity to a fixed wireless/cellular network on ground through trajectory design [11], [12].
UAS-BS placement optimization	Placement optimization with UAS and aerial balloons serving as relays/BSs under real propagation conditions [13], [14].
A2G/A2A propagation	Propagation measurements and practical channel models for various 3D UAS locations, environments, frequencies [15], [16].
UAS wireless security	Data/GPS signal jamming, side channel attacks, and physical layer security with UAS [17], [18].
Wireless localization/tracking	Localize, identify, track wireless devices/users at UAS based on RF signals [19], [20].
Multi-hop and ad hoc UAS networks	Range extension and intra/inter-swarm UAS communications for improved autonomy and reliability [21], [22].
Spectrum monitoring/sharing	Spectrum activity monitoring and sharing with agile/mobile UAS and balloons [23], [24].
Waveform design for UAS	Experiments with new waveforms to combat unique multipath/Doppler characteristics of UAS [25], [26].
UAS Detection & tracking	RF and radar based unauthorized / malicious / non-cooperating UAS detection, classification, and tracking [19], [27].
SDN, Cloud & edge comput.	Edge processing/caching at UAS, SDN for mesh UAS networking [28], [29].
IoT design & applications	Using UAS to monitor agriculture, environmental, infrastructure IoT sensors [30], [31].
Command & control	Communications, command, networking, autonomy protocols for multi-UAS flights in national airspace [19], [26].
UAS integration into cellular	UAS experiments with underlying 4G/5G cellular infrastructure and vehicular wireless infrastructure [3], [11], [32].

III. AERPAW Architecture

The fundamental testbed design requirements are: *reproducibility* of experiments, *usability* for quick on-boarding of new users, *interoperability* with other hardware and software, *programmability* of radios and networks, *open access* for diverse communities, and *diversity* of experiments and users. This section describes an architecture to realize our platform vision and above requirements. The proposed architecture provides a framework for subsequent platform design, development, deployment, and operation.

A. Testbed Architecture Overview

The fixed nodes, which may be deployed on rooftops or light poles, implement a terrestrial experimental network with access to each node for configuration, experimentation, and data collection through the AERPAW gateway. The fixed nodes may feature a combination of commercial-off-the shelf (COTS) SDRs, radars, custom radios, and other network elements. The modularity of the design allows physically swapping hardware components for others, including new prototypes, pre-market or early-market products. The mobile and aerial vehicles may carry SDRs, COTS UEs, and IoT systems. Different types of UAS models will carry as their payload various types of communication, processing and data collection systems.

Several open-source and commercial software libraries will be available for users, who can also install their own software or bring their own devices. Test procedures will be developed and expanded, depending on the platform user, to ensure safe operation. A realized platform shall fully automate managing access to resources, configuring and controlling the mobile and fixed nodes, as well as the experiments. Locally stationed platform and UAS operators will, at least initially, need to oversee experiments and handle complicated test cases.

Fig. 1 illustrates the proposed architecture at a high level.

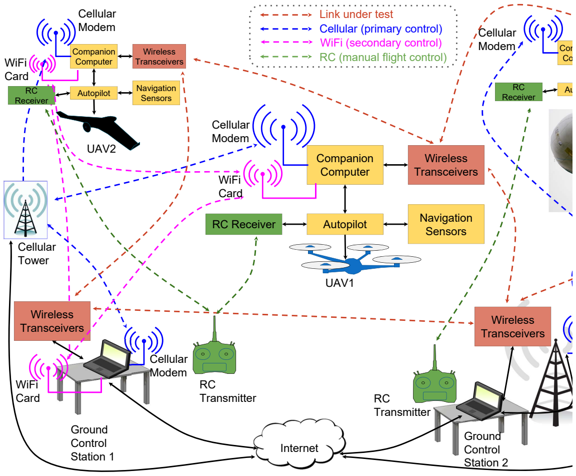

Fig. 1. Overview of the AERPAW testbed architecture

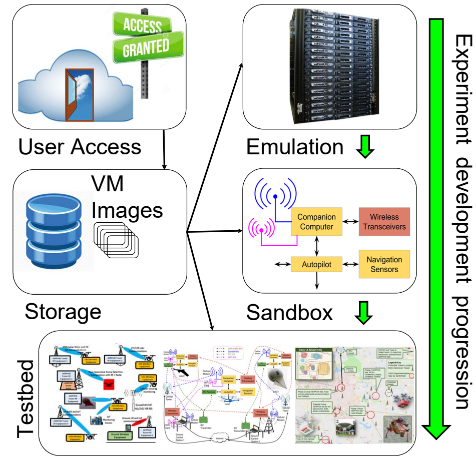

Fig. 2. Overview of the AERPAW management architecture.

The wireless enabled part of the testbed encompasses ground control stations (GCSs) and UAS. A GCS is equipped with a computer or connected to a data/processing center and radio equipment will provide the terrestrial network infrastructure. Other than to the computer, each GCS is also connected to the control plane either through fiber, where possible, or via a cellular modem.

An unmanned aerial system embraces the following logical components with exchangeable physical payloads.

a) Vehicle: A mix of multirotors, fixed wing aircrafts, and balloons, among others, as well as ground vehicles can be used as vehicles. Multirotor UAS are able to lift several kilograms of payload, reliably hover in a fixed position, and move predictably at fixed velocities. For experiments that need a longer endurance or longer range, AERPAW suggests fixed wing aircrafts or balloons, or the use of drone tethers. The ground vehicles are an inexpensive way to introduce mobility at ground level, emulating networked vehicular nodes.

b) Autopilot: Directly controlling the vehicle requires a dedicated autopilot, which typically consists of a small, light, embedded system that receives navigation sensor inputs, and controlling the vehicle position, orientation, and speed through pulse width modulated signals. Whereas in principle the autopilot function could be included in the companion computer, in our experience it is far better and safer to have a separate autopilot. It plays a crucial role in the UAS safety (e.g., by strict geofencing, monitoring altitude, remaining battery, GPS lock, wireless links, etc.) and thus should be provided as a separate system. We cannot entrust the autopilot image onto the companion computer, which will be under the testbed users' control. The *remote control (RC) receiver* plays an additional fail-safe role, where pilots on the ground will be able to abort the experiment (using an *RC transmitter*) for different reasons, and can take manual control of the UAS if required.

c) Companion Computer: The main role of the companion computer is to orchestrate and coordinate the UAS throughout testing. The companion computers need to be capable of significant processing power. In terms of software, the computers will use a Linux setup with container images that can be easily managed for uploading, downloading, and emulating. We will provide a base image with "hooks" allowing to change the default behavior to suit the user's need. The companion computer will communicate with the autopilot through MAVLink over USB. This will allow it to control the UAS position, orientation and trajectory, and to receive information from the navigation sensors.

d) Wireless Transceivers: Multiple experimental and operational radio systems and technologies may be available to users, as will be discussed in the next section. Where possible, the testbed operators shall control the wireless transceiver input and output, including logging through software, and stream the collected data to other points in the testbed.

e) Cellular Modems: All UAS and GCSs will be connected on the backplane to the same server through the cellular network. This server establishes a virtual switch, placing all elements in the same virtual subnet. It can also create a more general networking topology based on VLAN assignments, local virtual bridges and, if necessary, routers. The main advantage of using cellular systems for establishing the control links is their high availability and reliability.

B. Testbed Access and Experiment Support

Fig. 2 depicts an overview of the AERPAW management architecture. Using advanced Layer 2 services, all testbed sites will appear on a shared virtual LAN (VLAN).

a) User Management: Fixed and mobile radio platforms are networked and connected to the Internet through a gateway server. AERPAW proposes to leverage the federated authentication mechanism support available through Internet2. A user account and profile will serve for requesting access to resources, for scheduling experiments, for controlling access to resources, and for accounting.

b) Testbed Access: Most researchers remotely access a community testbed. Users can be provided with a customized view and front end by using commodity virtual machines (VMs) that are connected by VLANs to the UAS and radios assigned to them. The AERPAW VLAN with properly configured firewalls is key to secure testbed access. Using, for instance, OpenStack–a powerful open-source Infrastructure as a Service tool used by Amazon Web Services and recommended by ETSI's management and operation framework [33]–each project or experiment will be able to create the required virtual infrastructure with proper isolation. In other words, users shall be offered virtual resources, including virtual computing, networking and storage resources, for building virtual networks.

Some users will need physical access to the testbed, e.g. to test their custom radios. The architecture thus has to facilitate the seamless integration of new equipment.

c) Experiment Configuration and Execution: The experiment configuration and execution will largely be an exercise of creating, managing, executing, and retrieving VMs. Every node in the reserved slice of the experiment will run a VM whose image is entirely under the control of the experimenter. The experimenters will be presented with a number of default VMs for each network element.

Each VM in the experiment can be configured in two ways: the user can either directly configure a clone of a template VM residing in the experimenter space and then use the resulting VM in the experiment, or download an image template of the VM, configure it locally, create a new image and send it back for deployment. Here the user must also specify the physical nodes that the experiment needs. After successful experiment and code verification, discussed in Subsection III-C, the user submits the configuration files and the experiment can be scheduled.

d) Data: For most experiments, the data of interest may be distributed among different nodes. After the experiment, the VMs will be retrieved and the collected data accessible to the user. Internal storage servers or external Cloud services can be used for that.

e) Testbed Maintenance and Upgrades: The testbed needs to run common procedures and benchmarks to assess the proper functionality of the components and to calibrate them regularly. These procedures will run standard waveforms and other tests to check the RF as well as the computing and networking infrastructure. Testbed users may have access to such tests, which need to evolve as new hardware and software are added.

C. Emulation and Sandbox

We propose to make extensive use of *emulation* as a first step for familiarization with the testbed, as well as for allowing seasoned users to develop complex tests at minimal expense and risk. For safety and ease of development and verification of experiments, testbed users will develop their experimental software on an emulated platform, which is critical for verifying UAS navigation and control experiments. In the envisioned emulation system a VM will emulate each element in Fig. 1 that is needed for the experiment and the *exact same VMs* will be provided for the nodes in the testbed. Thus, each element in the testbed (computer, GCS, autopilot, wireless transceiver, control and RC links) will have a corresponding element in the emulator. The only element that will be simulated rather than emulated is the UAS including the navigation sensors, which will then be fed to the autopilot. Each link (e.g., the USB link between the companion computer and the autopilot, or the wireless transceivers) will be emulated with rate limited TCP or UDP flows. The main advantage of emulation is that the same VMs can run on the emulated system and on the real testbed.

TABLE II
AERPAW EXPERIMENTAL RADIO EQUIPMENT OPTIONS.

Equipment	Fixed Nodes	Mobile Nodes
SDRs	USRP X310/ N310/ mmW	USRP B210/ mmW
5G NR	5G BS	5G UE
RF Sensors	Keysight N6841A RF Sensor	Keysight Nemo RF Sensors
Radar	Fortem SkyDome	N/A
IoT	Sigfox Access Point	Sigfox Sensor
UWB	TimeDomain P410/ P440 radios	TimeDomain P410/ 440 radios

A second important step in the development of a successful experiment is using a sandbox, in essence a safe mini-testbed that replicates the systems carried by the mobile nodes with hardware in the loop capabilities of the autopilot. The main purpose of a sandbox is to validate the hardware side of the experiment.

The keys to success of the three step (emulation, sandbox, testbed) setup (Fig. 2) is the use of *identical* VMs in all three environments. Automated tools for deployment and retrieval of the VMs need to be provided to the users.

IV. AERPAW Radios

The AERPAW platform is expected to support experimentation with a variety of RF sensors, SDRs, COTS 4G and 5G BSs and UEs, IoT equipment, UWB and mmWave devices, as summarized in Table II. Several radios of each kind may be available to users at deployed testbed locations and portable to other sites.

a) Software Radios for Customizing Radios and Experiments: AERPAW suggests deploying COTS SDR hardware, such as different Universal Software Radio Peripheral (USRP) models, which provide powerful platforms for custom waveform and protocol development and testing. The team will leverage open-source software efforts, such as srsLTE and Open Air Interface to offer software templates and tools for rapid prototyping and testing of new radio access technologies. These radios can then be used to study aerial coverage, link quality, interference, etc., or to optimize waveforms, protocols, or the positions of aerial radio nodes for reliable UAS communications and networking.

b) 5G NR Network for Advanced Wireless Applications and Services: The envisaged 5G network is based on commercial networking equipment. A custom deployment for aerial network coverage and operation will be most valuable, allowing new services, such as command and control over cellular networks, to be developed and tested.

c) RF Sensors and Radars for Unauthorized UAS Detection and Tracking: The reliable detection, classification, and tracking of unauthorized UAS is a major concern and the corresponding technology will be an important component of UAS integration in the NAS. Whereas drone detection techniques based on acoustic sensors and computer vision exist, AERPAW suggests using RF sensors and radars.

d) IoT for Agriculture: Sigfox IoT devices will enable experimentation with fixed and aerial nodes. Since their coverage is wider and the BSs cost less, a Sigfox IoT access network can cover a significantly larger area than other technologies. Agriculture can benefit from these IoT deployments, where data from the sensors can be collected by the fixed or UAS BSs and processed at the edge or in the Cloud to drive effective decisions at much lower time scales.

e) UWB and WiFi Sniffers for Localization: UWB equipment can support short-range air-to-ground experimentation. WiFi sniffers can capture WiFi probe signals from ground nodes, with potential applications in search and rescue, or surveillance.

f) Custom Equipment: Users need to be able to deploy their own radio hardware or software, or both. These might be prototypes developed in an academic lab or supplied as industrial prototypes, pre-market or commercial products. The deployment is subject to size, weight, power, and regulation constraints, and has to be handled by defining proper integration and verification procedures.

V. Conclusions

This paper presents our vision of a UAS communications and networking testbed in a production-like environment. The proposed AERPAW architecture is meant as a blueprint for an experimental platform that would enable advanced wireless technology and systems research with UAS by offering diverse operational conditions and configurable radio scenarios to global researchers, developers, and other communities. The use of diverse and software-programmable radio access and networking technologies will allow for flexible testbed configurations to meet the emerging R&D and community needs.

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